Analysis and Design of Tunable Microwave Microstrip Devices using Soft Computing

A

Synopsis

Submitted in the partial fulfilment for the requirement of

Doctor of Philosophy

In

Physics

Submitted by

Ritika

Under the supervision of

Dr. Ashok Jangid

Associate Professor

Department of Physics and Computer Science

DEPARTMENT OF PHYSICS AND COMPUTER SCIENCE, FACULTY OF SCIENCE
DAYALBAGH EDUCATIONAL INSTITUTE (DEEMED UNIVERSITY)
DAYALBAGH, AGRA-282005

2021

1. Introduction

The rapid growth of wireless communications systems and digital media has been one of the most exciting developments in electronics during recent years. 5G represents a new era in which wireless connectivity reaches everything, with the Internet of Things (IoT) creating a revolution in almost every face of modern life, including healthcare, smart cities, energy, robotics, manufacturing, retail and the creative industries. Radio frequency (RF) waves and microwaves play an important role in modern day to day life. The RF and microwaves wireless technologies have many commercial and military applications. The most important applications are communications, radar, navigation, surveillance, medical, remote sensing, broadcasting, automobiles and highway sensors, and astronomy and space research. The microwaves are electromagnetic (EM) waves with frequencies ranging from 300 MHz to 300 GHz, which refers to the wavelengths from 1m to 1mm in free space. The EM waves with frequencies ranging from 30 GHz are also called millimeter waves because their wavelengths are in millimeter range (1- 10 mm). The increasing demand to frequency channels has created crowding of microwave spectrum but by the availability of millimeter waves there is unused frequency space which can be used (Hong & Lancaster, 2002).

Modern telecommunication systems have become multi-standard, having multiband coverage and vast functionality nowadays. Thus, they need a wide variety of analog circuits which comprises several amplifiers, filters, oscillators, antennas etc., for specific purposes. Filters play vital roles in various RF/microwave applications. These applications continue to challenge RF/microwave filters with ever more tough requirements – higher performance, smaller size, lower cost, and lighter weight. The EM spectrum is limited and has to be shared, thus filters are used to select or confine the RF/microwave signals within given spectral limits. There are many applications which require diversity in filter performance. As per the requirements and specifications, microwave filters may be designed as lumped element or distributed element circuits and they may be realized in various transmission line structures, such as coaxial line, waveguides, and microstrip(Hong & Lancaster, 2002). Due to the reduction in size of circuits with integrated semiconductor devices in microwave domain, there is a need of transmission structure that was compatible with circuit construction techniques to provide guided waves over limited distances. Grieg and Engelmann in 1952 proposed this with a planar form

of single wire transmission line over a ground plane, called microstrip line (Grieg & Engelmann, 1952). After the rapid development of the technology, microstrip line structure has found an increasing use in microwave integrated circuits (MICs) and monolithic MICs (MMICs). Microstrip line is a wide band transmission system in which the EM waves propagate through a dielectric medium bonded by a conducting strip on one side and a conducting ground plane on the other side such that the distance between the conducting strip and the ground plane being a small fraction of the wavelength of the line (Arditi, 1955).

A microstrip filter is a two port network used to control the frequency response for a specific purpose in a microwave system by facilitate transmission at frequencies within the passband and attenuation in the stopband of the filter. Parallel Coupled Microstrip Filters (PCMF) is widely used in microwave systems (Pozar, 2005). In recent time microstrip patch antennas have been used broadly in numerous civil and military applications. These applications are such as mobile communications, radars, satellites, sensors and also in some new fields like medicine and biology. The microstrip patch antenna has been widely used because of its inherent characteristic advantages such as planar configuration, low profile, low weight, and simple integration of passive and active devices. They are also functional at multiple frequency bands and allow both linear and circular polarization (Garg, Bhartia, Bahl, & Ittipiboon, 2001). These attractive features have increased the application of microstrip antennas and stimulated greater effort to investigate their performance. Microstrip antennas have been used in different configurations such as square, circular, rectangular, triangular, trapezoidal, elliptical, etc. Circular microstrip patches can be used as resonant antennas and also as planar resonators for filters and oscillators in microwave integrated circuits (MICs) (Wong, 2002). Since the frequency spectrum is limited, there is a need of smart usage of the available resource. Thus, there is a need of high performance RF/microwave tunable filters in reconfigurable systems to facilitate efficient utilization of the available frequency spectrum.

Tunable filters are essential for multiband communication systems and have been extensively studied in recent years. The need for tunability and configurability in wireless systems stand up when positioning different systems that coexist geographically. Such arrangements occurs when an operator has already installed a network and requires to add a new generation network. This can be explained

as adding a fourth-generation (4G) network to an existing third-generation (3G) network or a 5G network to an existing 4G network. The benefits of tunable hardware also facilitate the network system to efficiently manage hardware resources while accommodating multi-standard necessities and achieving network traffic optimization. Tunable filter technologies also benefit wireless systems in other areas. With the help of tunable filters, one installation can serve many years. The ideal tunable filter must inherent properties such as high loaded Q value, wide tuning range, high tuning speed, good linearity, small size and mass, high reliability, and high power handling capability (Richard, Chandra, & Raafat, 2007) However, tuning is very important in the fabrication of complex microwave filters.

Tuning of any manufactured microwave device is almost necessary due to the lack of highly accurate design models, manufacturing tolerances, and design uncertainties. The information regarding design, evaluation, realization, etc. for most of the real world control/tuning problems, can be classified into two types which are numerical information obtained from mathematical models or measurements, and linguistic information obtained from human experts. Soft Computing (SC) methods provide distinct advantages for the design problems of different disciplines including microwave and millimeter wave domain problems. Soft computing is referred to a collection of computational techniques in computer science, artificial intelligence and related fields, whose aim is to study, model, and analyse very complex phenomena for which more conventional (hard computing) methods have not obtained low cost, analytic, and complete solutions (Pratihar, 2008). It was introduced in 1992 by Prof. L. A. Zadeh, University of California, who proposed that the aim of soft computing is to tolerate imprecision, uncertainty, and approximation in order toachieve robust and low cost solution in small time frame. Soft computing was restricted to mainly three techniques which are Artificial Neural Network (ANN), Genetic Algorithm (GA), and Fuzzy Logic (FL) (Zadeh, Forward. In: Proceedings of the Second International Conference on Fuzzy Logic and Neural Networks, 1992). ANN has been widely used for fast microwave modelling but it has also suffered with generalization problems. Due to which there is a need to develop novel modifications and hybridizations of soft computing methods in order to solve RF/microwave design problems effectively and efficiently. Hybrid Intelligence System deals with synergistic integration of two or more of the technologies as shown in Figure 1.

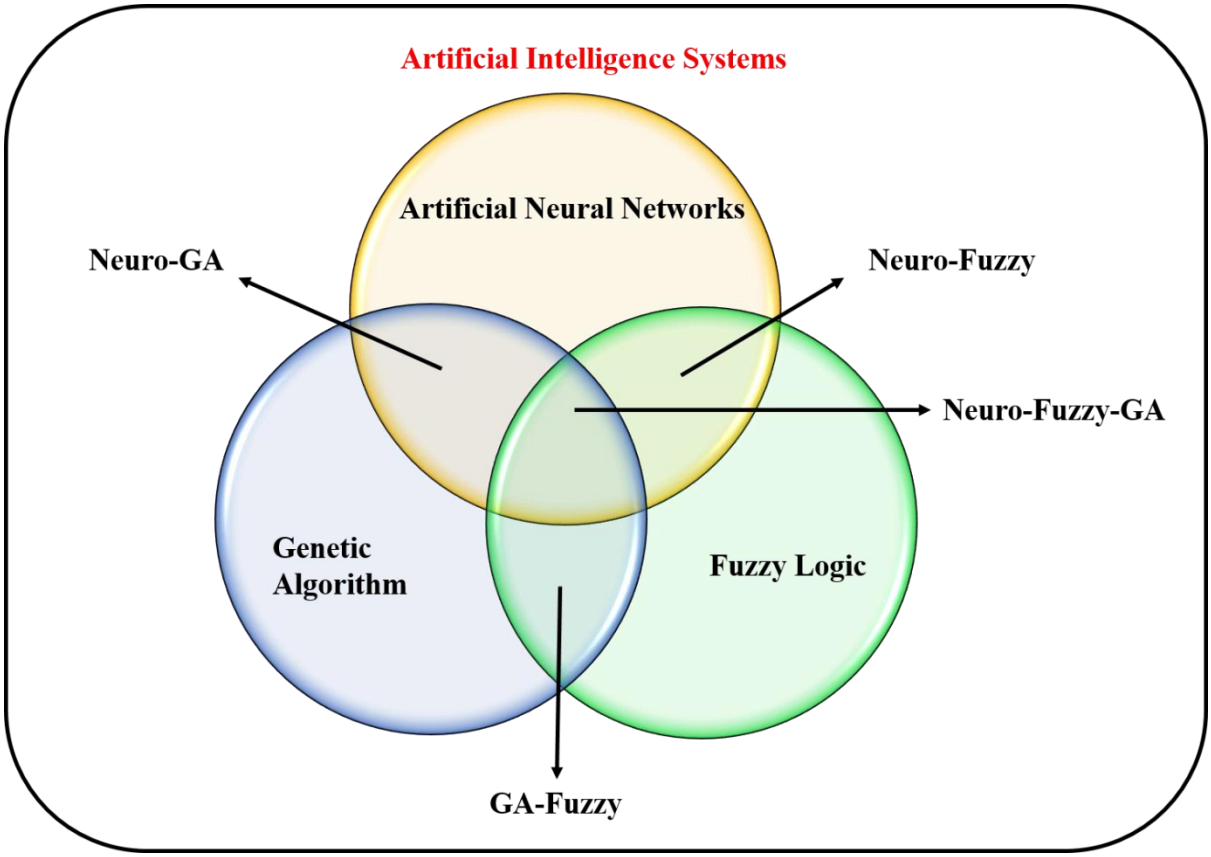

Figure 1 Integration of Neural Networks, Fuzzy Logic and Genetic Algorithm Technologies.

Recently, hybrid methods combining coarse models (CMs) with the accuracy of fine models (FMs) by means of artificial neural networks (ANNs) have been developed to model microwave devices. However, these methods have a principal drawback such as it is difficult to extract and understand the knowledge acquired by the ANNs. And to overcome this drawback the ANN in the hybrid neural methods have been substituted by an Adaptive Neuro-Fuzzy Inference System (ANFIS) (Jang, 1993). The purpose of ANFIS is to calculate accurately the quasi-static parameters of microstrip lines. The ANFIS is a class of adaptive networks which are functionally alike to fuzzy inference systems (FISs). Thus, it is the combination of powerful features of FISs with those of artificial neural networks (ANNs).

Artificial neural network (ANN) is a powerful technique in microwave modelling and design (Zhang, Gupta, & Devabhaktuni, “Artificial neural networks for RF and microwave design – from theory to practice”, 2003; Kabir, et al., 2010; Root, 2012). There are wide application range in the field of parametric modelling of microwave components (Na, Feng, Zhang, & Zhang, 2017; Cao, Wang, & Zhang, “A new training approach for parametric modelling of microwave passive components using

combined neural networks and transfer functions", 2009; Feng, Reddy, Zhang, Ma, & Zhang, 2017), nonlinear microwave device modelling (Root, 2012; Liu, Na, Zhu, Ma, & Zhang, 2017; Zhu, et al., 2016), power amplifier modelling (Isaksson, Wisell, & Ronnow, 2005; Mkadem & Boumaiza, 2011), coplanar waveguide (CPW) circuit modelling (Watson & Gupta, 1997), microwave circuit optimization (Rayas-Sanchez, 2004), and microwave component designs (Kabir, Wang, Yu, & Zhang, 2008; Cao, Reitzinger, & Zhang, "Simple and efficient high dimensional parametric modelling for microwave cavity filters using modular neural network", 2011). Training a neural network to directly model the original electromagnetic (EM) problem with electrical parameters as outputs and geometrical or physical parameters as inputs can be called the forward modelling. For the application of microwave component design or tuning, the inverse problems usually need to be solved to obtain corresponding geometrical or physical parameters from the given electrical parameters. The inverse problems are usually solved by two kinds of methods, i.e. optimization method and the inverse modelling method (Kabir, Wang, Yu, & Zhang, 2008). Contrary to the forward model, the outputs of the inverse model are geometrical or physical parameters and the inputs to the inverse model are the electrical parameters. The developed inverse model can be beneficial in directly obtaining the values of the geometrical or physical parameters from the given electrical parameters. Unlike the optimization-based method, the inverse modelling method does not need to iteratively evaluate the forward model. Therefore, the inverse modelling method is much more efficient than the optimization-based method (Koziel & Bekasiewicz, 2016).

2. Literature Review

Literature review describes the background and development scenarios of proposed work. This section review the literature on microstripdevices, followed by tunablemicrostrip devices and then the review of Soft computing methods in tabular form:

Table 1: Literature review of different research paper in three domains.

DOMAIN	AUTHORS	FINDINGS
Microstrip Devices	(Al-Yasir, Abd-Alhameed, Noras, Abdulkhaleq, & Ojaroudi, 2018)	A compact microstrip band-pass filter (BPF) covering the 3.4-3.8 GHz spectrum bandwidth for 5G wireless communications is presented. The planar filter uses three resonators, each terminated by a vias to hole ground at one end and a capacitor at the other end with 50Ω transmission line impedances for input and output terminals. The coupling between the lines is adjusted to resonate at the centre frequency with third-order band-pass Butterworth properties. The proposed combline filter is designed on an alumina substrate with a relative dielectric constant of 9.8 and a very small size of 9 × 5 × 1.2 mm^3. This filter can be easily tuned in frequency by adjusting the capacitors.
	(Yang, Psychogiou, & Peroulis, 2018)	The authors reported the design and optimization of reconfigurable cavity bandpass filter using MEMS switches with continuously tunable resonant frequency over a wide tuning band. The tunable filters are implemented by using silicon micro-matching methods, which enables them to be tuned with the desired frequency in the millimetre wave (28-90 GHz) band. Besides, a novel feeding technique is used with fully passive input and output impedance matching over the total tuning range.
	(Boukarkar, et al., 2017)	In this paper, three major concepts are combined together to design a highly integrated tunable triple-band patch antenna. Firstly, two properly U-slots are cut from the same broadside patch antenna to introduce two band notches leading to a triple-band function. Secondly, the size reduction is obtained by shorting one patch edge using metalized vias. Finally, the tuning performance is realized by properly inserting three varactor diodes into the antenna radiating patch. The proposed design is a highly integrated antenna with extreme stability of the operating frequencies and similar unidirectional radiation patterns during the frequency tuning of three operating frequencies.
	(Richard, Chandra, & Raafat, 2007)	This book presents important developments in network synthesis and practical implementations of microwave resonator circuits over previous years. It delivers a convenient and clear description of system characteristics and focuses on microwave resonator filters, basic requirements in the concept and theory of microwave resonator filters, up to recent techniques of network synthesis. This review is the most comprehensive includes important design techniques concerning the study of coupling matrices. Thus, it is very useful book for every microwave device researcher.
	(Ramadan, et al., 2014)	In this paper, there is a proposed model of frequency-tunablemicrostrip antennas, for cognitive radio application. The approach is based on electrically tuning the antenna's operating frequency by integrating

		reconfigurable band pass filters into wideband antenna structures. The design of an open loop resonator (OLR)-based bandstop filter, and its transformation to a bandpass filter, are investigated first.
Methods of tunability	(Tanani & Rebeiz, 2010)	This paper describes two planar RF-MEMS tunable filters designed specifically as a demonstration of this technology for wireless bands. The design employs a distributed capacitive coupling between the resonators, which results in a constant absolute bandwidth over the tuning range while still using a short electrical resonator length. A new wideband transformer circuit is used to achieve excellent impedance matching across the 1.5-2.5 GHz band without the need for tuning elements in the input transformer.
	(Chen, Li, & Chen, 2018)	In this paper, a tunable dual-band bandpass-to-bandstop filter and its analysis are proposed. The bandpass-to-bandstop transformation could be obtained by changing the state of the p-i-n diode. Using two sets of half-wavelength resonators loaded with varactors, the centre frequency of each band can be tuned independently by adjusting the varactors. In order to achieve the controlling of the external quality factors (Q_e) for the bandpass mode, the feeding lines are loaded with two varactors and wide tuning range of Q_e can be obtained.
Application of Soft Computing	(Zhang, Gupta, & Devabhaktuni, "Artificial neural networks for RF and microwave design – from theory to practice", 2003)	Computational modules of neural network have recently gained attention as an unconventional and useful tool for RF and microwave modelling and design. Neural networks can be trained to learn the behaviour of passive/active components. A trained neural network can be used for high-level design, providing fast and accurate answers to the task it has learned. Neural networks are much beneficial than conventional methods in so many ways such as numerical modelling methods, which could be computationally expensive, or analytical methods which could be difficult to obtain for new devices, or empirical modelling solutions whose range and accuracy may be limited.
	(Kabir, et al., 2010)	This paper presents microwave filter modelling, optimization and design methods using artificial neural network (ANN) technique. The ANN method provides fast and accurate results and reduces the computational costs associated with a time consuming EM solver in the design methods to design complex microwave filters. Various ANN structures including wavelet and radial basis function have been utilized for this purpose. It helps to improve the speed and accuracy of filter design for communication circuits and systems.
	(Zhang, Jin, Na, Zhang, & Yu, 2018)	This paper describes a new method for artificial neural network (ANN) inverse modelling and applications to microwave filters. In inverse modelling of a microwave components, the inputs to the model are electrical parameters such as S-parameter, and the outputs of the model are geometrical or physical parameters. Since the analytical formula of the inverse input-output

		relationship does not exist, the ANN becomes a logical choice, because it can be trained to learn from the data in inverse modelling. The main challenge of inverse modelling is the non-uniqueness problem. This problem in the ANN inverse modelling is that different training samples with the same or very similar input values have quite different (contradictory) output values (multivalued solutions).
	(Rahouyi, Hinojosa, & Garrigos, 2006)	The aim of this paper is to suggest a solution to the existing disadvantage of ANN. The ANN method decrease the cost of needed data, improve generalization ability, and are suitable for highly nonlinear and complex microwave devices. However, these methods have a principle drawback. It is difficult to extract and understand the knowledge acquired by the ANNs. Thus they presented a new technique by substituting ANN in the hybrid neural methods by an adaptive neuro-fuzzy inference system (ANFIS). However, better results can be obtained by using the ANFIS in solving these problems because the ANFIS is a very effective modelling scheme combining the benefits of both ANNs and FISs in a single model. ANFIS models which can be developed from measured/simulated antenna data, provide us accurate, fast and reliable services. Once developed, these ANFIS models can be used in place of traditional as well as computationally intensive numerical models to speed up antenna design.

3. Motivation

Currently, several microwave filter designs are in demand for use in wireless communications. The reconfigurable planar filter among various microstrip filters grants more advantages and better prospects for communication applications, by inheriting the properties of being compact in size, light-weight and cost-effective. Traditional filters have disadvantage of occupying much space on circuit boards. With the implementation of tunable filter, number of switches between electronic components can be reduced which leads to saving space and improving performance. Communication satellite operators are beginning to use more and more reconfigurable payloads to adapt to changing markets over the 15 year lifetime of satellites. This is being made possible by the advances in digital technology, steerable multi spot beams, reconfigurable phased array antennas and flexible traveling wave tube amplifier technology. Another element of flexibility is the ability to choose RF channel bandwidths to satisfy a particular set of customer requirements over the lifetime of the satellite. This is being made possible by the advancers in frequency and bandwidth controllable tunable filter

networks. Use of tunable filters would also allow sharing of hardware resulting in reduced mass for the payload (Richard, Chandra, & Raafat, 2007).

Much of the soft computing techniques have been inspired from biological phenomena and the social behaviour of biological populations. The term of soft computing was confined to mainly three techniques such as Artificial Neural Network (ANN), Genetic Algorithm (GA) and Fuzzy Logic (FL). Soft Computing methods such as Genetic Algorithm (GA), Artificial Neural Network (ANN) and Fuzzy Logic (FL) are highly in demand and so they have been widely used by EM researchers for microwave design from a very long time. Soft computing methods play important role in the design and optimization of many engineering disciplines including microwave domain. To achieve robust and low cost solution in a small time frame, the aim of these methods is to tolerate imprecision, uncertainty, and approximation. However, these methods suffer from certain drawbacks. GA is a powerful optimization tool, but it requires a large number of iterations to achieve convergence and to arrive at an optimum solution. ANN has proved its efficiency in modelling microwave components, but it has also suffered with generalization problems. Moreover, due to very small wavelengths involved in microwave design, which requires high precision, it is not easy to model components using conventional methods (Chauhan, Kartikeyan, & Mittal, 2012).

Previously, ANNs have been widely used to solve antenna and electromagnetic engineering problems as a fast, accurate, and flexible method (Zhang & Gupta, "Neural Networks for RF and Microwave Design", 2000). However, better results can be obtained by using the ANFIS in solving these problems because the ANFIS is a very effective modelling scheme combining the benefits of both ANNs and FISs in a single model. ANFIS models which can be developed from measured/simulated antenna data, provide us accurate, fast and reliable services. Once developed, these ANFIS models can be used in place of traditional as well as computationally intensive numerical models to speed up antenna design. ANFIS is also less susceptible to the noise inherent in measured data and antenna imperfections (Bokshtein, Shmaltz, Herbst, Bunke, & Kandel, 2000).

The ANN can learn the nonlinear relationships between the behaviours of microwave devices and the geometrical/physical parameters. The ANN trained to model the original microwave device problems can be called forward model, where the inputs to the model are the geometrical or physical parameters

and the outputs of the model are the electrical parameters. For design purposes or tuning of microwave filters, the information is often processed in the reverse direction in order to find the geometrical or physical parameters from given electrical parameters, which is called the inverse problem (Kabir, Wang, Yu, & Zhang, 2008). For a given electrical target, the forward models will be evaluated iteratively to find the optimal geometrical parameters, such that the circuit response matches the electrical target. Furthermore, for different electrical targets, this optimization process to find the geometrical or physical parameters will be repeated again and again, which is time-consuming. In inverse modelling, the electrical parameters are defined as the inputs to the model and the geometrical or physical parameters are defined as the outputs of the model. Once the inverse model is obtained, it can provide the geometrical parameters immediately without iteratively evaluating the model for given electrical parameters. This method is much faster than the conventional iterative optimization process and can afford to be used in repetitive designs or parameter extraction process (Kabir, Wang, Yu, & Zhang, 2008).

4. Objectives

The specific objectives of the proposed work are outlined as follows:

1. To develop soft computing model for analysis of microwave microstriptunable devices like filters, antennas, etc.
2. To solve inverse modelling problem of tunable microwave microstrip devices using soft computing.
3. To explore possibilities of fast and accurate hybrid models of soft computing and numerical techniques for design and development of tunable microwave structures.
4. To compare the simulated results with various experimental and theoretical results to validate the proposed models and approaches.
5. To compare and validate design tunable microwave microstrip circuits using commercially available simulators.

5. Soft Computing

Soft computing (SC) technique refers to the field in computer engineering that is characterized by using uncertain, imprecision and approximation solutions to computationally hard problems related to

the area of science, medicine, management and humanities etc. Soft computing can be categorized in two broad components as approximate reasoning and randomized or functional search. The SC methods can be beneficial in many ways such as it can be easily interfaced with many of the EM simulators due to which the laborious task of optimizing design parameters in manual mode can be converted to computer simulations. Hence faster results can be obtained (Chauhan, Kartikeyan, & Mittal, 2012).

5.1 Artificial Neural Networks

The concept of artificial neural network is based on the mathematical model of human brain which can perform sophisticated and intelligent computations in very fast manner (Rajasekaran, Thiruvenkatasamy, & Lee, "Tidal level forecasting functional and sequencial learning neural networks", 2005). An artificial neural network is a mechanism which is designed to model the technique, in which the brain executes a particular chore or purpose of interest, the network is typically implemented by simulated software as in digital computer. To understand the basic function of ANN, it is necessary to have a look at human brain.

A human brain consists of around 10^{11} computing rudiments known as neurons. A neuron consists of a cell body to sum and sill those incoming signals, dendrites are to carry electrical signals into cell body and an Axon helps in transferring signal from one neuron to other neurons. These signals are communicated from one neuron to other by Synapse which connects an axon of one soma cell and a dendrite of another cell (Zurada, 1995).

The analogous model of biological neurons shown in Figure 5.1 is called artificial neuron. Inspired by the arrangement of the human brain, an ANN also made of a set of extremely consistent of dispensation units, known as nodes. Every node is planned to imitate its natural complement, the neurons. Each one also accepts a weighted sum of inputs and results as an output. Artificial neural network also resembles the genetic neuron for collecting information from knowledge by example to store this information within buries neuron association power called weights. These similarities of organic neural cell, the unit of configuration of ANN is the neuron which is made by summing of inputs with a transfer function depicted in Figure 2 in which the inputs are x_1, x_2, x_3, …… x_n of the neuron and their analogous weights of w_1, w_2, w_3, …… w_n. It represents the relations in organic nets

and takes action to decrease or increase the contributions of signals of neuron. Now and again a bias 'b' is summed up into the inputs. In general the inputs, outputs, weights and biases could be authentic numeric value, binary value or bipolar values. They are multiplied by their analogous weights and the added mutually to make the output of the neuron and says net. This can be of this form:

$$\text{Net} = \sum_{i=1}^{n} w_i x_i + b = w_1 x_1 + w_2 x_2 + w_3 x_3 + \cdots + w_n x_n + b \quad (1)$$

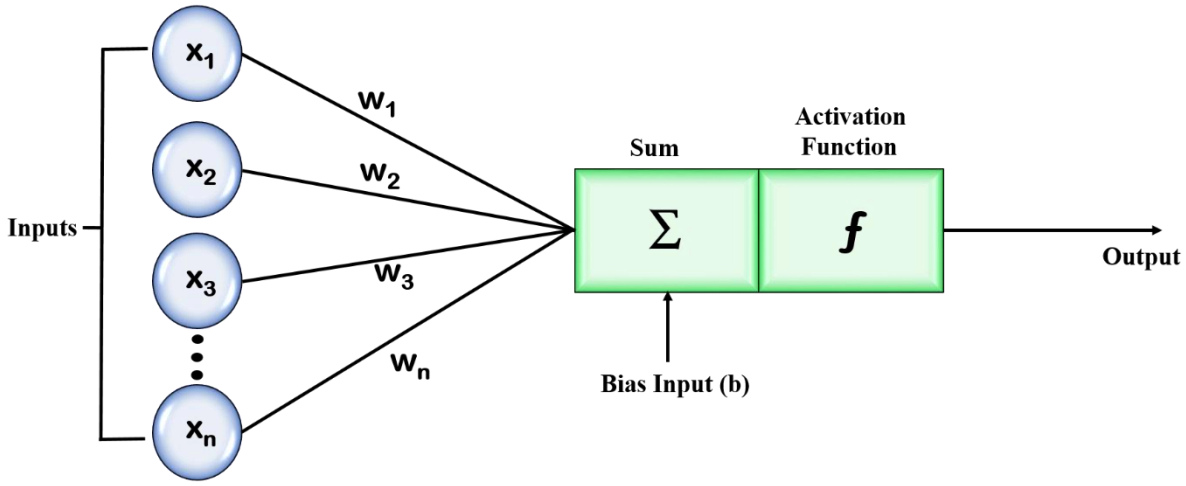

Figure 2 The simple model of an artificial neuron.

These neuron are acts as a function f of net to give an output y and can be shown inequation form as:

$$y = f(\text{net}) = f\left(\sum_{i=1}^{n} w_i x_i + b\right) \quad (2)$$

in which function f is called the activation (or it is also called transfer function).

Inverse Modeling Techniques

The ANN can learn the nonlinear relationships between the behaviours of microwave devices and the geometrical/physical parameters. The ANN trained to model the original microwave device problems can be called forward model, where the inputs to the model are geometrical or physical parameters and the outputs of the model are the electrical parameters. For design purposes or the parameter extraction of microwave filters, the information is often processed in the reverse direction in order to find the geometrical or physical parameters from given electrical parameters, which is called the inverse problem. There are usually two ways to solve the inverse problem i.e., the optimization method and inverse modelling method. The optimization method is the most conventional way (Jin, Zhang, & Zhang, 2016). For a given electrical target, the forward models will be evaluated iteratively to find the optimal geometrical parameters, such that the circuit response matches the electrical target.

Furthermore, for different electrical targets, this optimization process to find the geometrical or physical parameters will be repeated again and again, which is time-consuming.

The other way to solve the inverse problem is the inverse modelling method (Kabir, Wang, Yu, & Zhang, 2008). In inverse modelling, the electrical parameters are defined as the inputs to the model and the geometrical or physical parameters are defined as the outputs of the model. Once the inverse model is obtained, it can provide the geometrical parameters immediately without iteratively evaluating the model for give electrical parameters. This method is much faster than the conventional iterative optimization process and can afford to be used in repetitive designs or parameter extraction process(Koziel & Bekasiewicz, 2016).

5.2 Evolutionary Algorithm

Evolutionary algorithms includes a set of problem-solving techniques based on the principles of biological evolution. The main components of evolutionary computation includes genetic algorithms, genetic programming, evolutionary strategies, evolutionary programming. Genetic algorithm (GA) are evolutionary search and optimization algorithms based on the mechanics of natural selection and natural genetics. GA is different from most traditional optimization methods. The major difference between GA and other traditional search methods is that it starts with a set of solutions in contrast to the single solution approach used by traditional optimization methods (Rajasekaran & Pai, 2006).

5.3 Fuzzy Logic

Most current intelligent control approaches combine the standard processing methods using the numerical data with expert information into the control/tuning problem. Fuzzy set theory (FST) was first introduced by L. A. Zadeh(Zadeh, "Fuzzy Sets", 1965). In classical logic, sets are defined in a crisp manner, i.e., an element either belongs to a set or does not belong to it. In fuzzy logic (FL), a membership value between “0” and “1” is assigned to each element of the set. When the element does not belong to the set then it represents “0”, whereas if the element totally belong to the set then it represents “1”. Fuzzy logic interprets the numerical data as linguistic rules. The extracted rules will then be used as a kind of system specification to calculate the output values of the system. The procedure of creating fuzzy sets from numerical data is called “fuzzification,” and the process of

calculating the output values from the output fuzzy sets based on some linguistic rules is called "defuzzification" (Wang & Mendel, 1992).

6. Adaptive Neuro-Fuzzy Inference System (ANFIS)

The class of adaptive networks which are functionally equivalent to fuzzy inference systems (FISs) represents ANFIS. It is the combination of both the powerful features of FISs with those of artificial neural networks (ANNs). A hybrid learning (HL) algorithm based on the least square method (LSM) and the back propagation (BP) algorithm is used to identify the parameters of ANFIS. The features of neuro-fuzzy systems have made it popular in recent years which includes fast and accurate learning, excellent explanation facilities in the form of semantically meaningful fuzzy rules, the ability to accommodate both data and existing expert knowledge about the problem, and good generalization capability (Jang, 1993).

The ANFIS is a very powerful approach for building complex and nonlinear relationship between a set of input and output data. It combines the explicit knowledge representation of FIS with the learning power of ANNs. Usually, the transformation of human knowledge into a fuzzy system (in the form of rules and membership functions) does not give exactly the target response. So, the optimum values of the FIS parameters should be found (Jang, 1993). The main objective of the ANFIS is to determine the optimum values of the equivalent FIS parameters by applying a learning algorithm using input– output data sets. The parameter optimization is done in such a way that the error between target and actual output is minimized.

The ANFIS architecture consists of fuzzy layer, product layer, normalized layer, de-fuzzy layer, and summation layer. A typical ANFIS architecture is shown in Figure 3, in which a circle indicates a fixed node, whereas a square indicates an adaptive node. For simplicity, we assume that the FIS under consideration has two inputs *x* and *y* and one output *z*. The ANFIS used in this work implements a first-order Sugeno fuzzy model (Sugeno & Kang, 1988). Among many FIS models, the Sugeno fuzzy model is the most widely applied one for its high interpretability and computational efficiency, and built-in optimal and adaptive techniques. For a first-order Sugeno fuzzy model, a common rule set with two fuzzy if-then rules can be expressed as

$$\text{Rule 1: If x is } A_1 \text{ and y is } B_1, \text{ then } z_1 = p_1x + q_1y + r_1 \quad (3)$$

Rule 2: If x is A_2 and y is B_2, then $z_2 = p_2x + q_2y + r_2$ (4)

where A_i and B_i are the fuzzy sets in the antecedent, and p_i, q_i, and $r_i$are the design parameters that are determined during the training process.

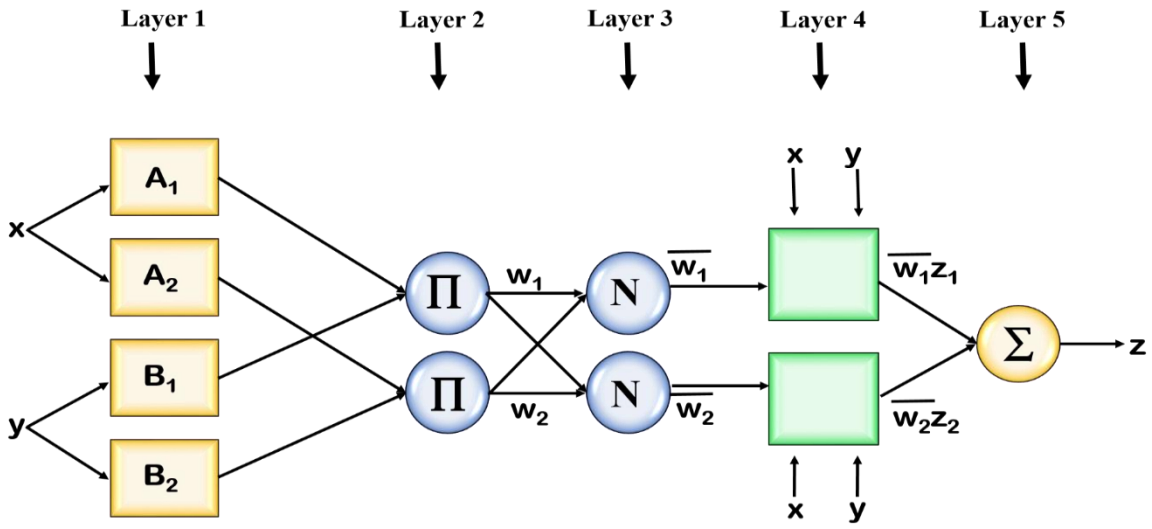

Figure 3 Architecture of ANFIS.

7. Work Plan and Methodology

Before running the design, it is important to identify the steps of each process to ensure the performance of the filter design. For the proposed research a tunablemicrostripdevice is need to be designed, then there will be a comparison to the conventional models. The study will be done by using microstrip line calculator to check the filter design proposed. The overall design process was done by using commercially available professional platforms such as CST, MATLAB, etc.The following steps describes the overall design procedures of this research.

STEP 1: Literature Survey- A detailed study of the literature has been done to take stock of the existing works so far in this field. The literature survey will include two parallel surveys. In one survey, study of the various stuructures of different types of microwave devices are to be done and their performance are to be analysed whereas on the other survey, the study will include the study on various processes of soft computing including artificial neural networks, fuzzy logics, genetic algorithms and some hybrid intelligence systems.

STEP 2: Data Collection- in the proposed work, various sets of data for different microwave devices

will be collected from some published research papers or from some books or from some professional platforms like CST, etc.

STEP 3: Designing Neural Network- With the help of the collected data now we will design a neural network model in MATLAB. As performance or operating band of frequency of devices depend on the design parameters like dimensions of ground plane, dimensions of radiating element, type of materials used, dielectric constant of the substrate, substrate thickness etc., hence different frequency bands can be obtained by varying one or more design parameters. Taking different combinations of design parameters, sets of data are to be collected.

STEP 4: Training of Model- Once a network has been structured for a particular application, that network is ready to be trained. To start this process initial weights are chosen randomly. Then the training begins.

STEP 5: Validation of the Model- In the training section, we trained our neural network model on the selected data sets, and it seemed to reach a reasonable loss and accuracy. If the model can take what it has learned and generalize itself to new data, then it would be a true testament to its performance. If the error is minimum we go for fabrication otherwise we take another set of data and restart the process of designing the model.

STEP 6: Simulation using Professional Simulators- Professional simulators which are commercially available in market such as CST, etc. are used to perform all the simulations. These solvers allow users to monitor various results for radiation patterns, return loss (S- parameters), voltage standing wave ratio (VSWR), input impedance and Smith's Chart. Results can be validated by using some professional simulators and published data in literature.

STEP 7: Fabrication- Using one simulated data, a prototype model will be fabricated.

STEP 8: Measurements- After the fabrication process of the device is complete, the device are ready for measurement. The measured results are compared with the simulated results. The measured results are expected to be similar to that of simulated results.

References

Al-Yasir, Y., Abd-Alhameed, R., Noras, J., Abdulkhaleq, A., & Ojaroudi, N. (2018). “Design of very compact combline bandpass filter for 5G application”. *In Proceedings of the 2018 Loughborough Antennas & Propagation Conference (LAPC),* (pp. 12-13). Loughborough, UK.

Arditi, M. (1955). “Characteristics and applications of microstrip for microwave wiring”. *IEEE Transactions Microwave Theory Techniques, 3*, 31-56.

Bokshtein, E., Shmaltz, D., Herbst, O., Bunke, H., & Kandel, A. (2000). “Monopulse amplitude direction-finding using neuro-fuzzy approach”. *Robotics Autonomous System, 33*, 125-134.

Boukarkar, A., Lin, X., Yu, J., Mei, P., Jiang, Y., & Yu, Y. (2017). “A highly integrated independently tunable triple-band patch antenna”. *IEEE Antennas and Wireless Propagation Letters, 16,* 2216-2219.

Cao, Y., Reitzinger, S., & Zhang, Q. (2011). "Simple and efficient high dimensional parametric modelling for microwave cavity filters using modular neural network". *IEEE Microwave Wireless Components Letter, 21*(5), 258-260.

Cao, Y., Wang, G., & Zhang, Q. (2009). “A new training approach for parametric modelling of microwave passive components using combined neural networks and transfer functions”. *IEEE Transactions Microwave Theory Techniques, 57*(11), 2727-2742.

Chauhan, N., Kartikeyan, M., & Mittal, A. (2012). *“Soft Computing Methods for Microwave and Millimeter-Wave Design Problems”.* Verlag Berlin Heidelberg : Springer.

Chen, F., Li, R., & Chen, J. (2018). “A tunable dual-band bandpass-to-bandstop filter using p-i-n diodes and varactors”. *IEEE Access, 6*, 46058-46065.

Feng, F., Reddy, V., Zhang, C., Ma, J., & Zhang, Q. (2017). “Parametric modelling of microwave components using adjoint neural networks and pole-residue transfer functions with EM sensitivity analysis". *IEEE Transactions Microwave Theory Techniques, 65*(6), 1955-1975.

Garg, G., Bhartia, P., Bahl, I., & Ittipiboon, A. (2001). *“Microstrip Antenna Design Handbook”.* Canton: Artech House.

Grieg, D., & Engelmann, H. (1952). “Microstrip – A new transmission technique for the kilomegacycle range”. *Proc IRE, 40*, 1644-1610.

Hong, J., & Lancaster, M. (2002). *"Microstrip Filters for RF/Microwave Applications"*. John Wiley & Sons, Inc.

Isaksson, M., Wisell, D., & Ronnow, D. (2005). “Wide-band dynamic modelling of power amplifiers using radial-basis function neural networks”. *IEEE Transactions Microwave Theory Techniques, 53*(11), 3422-3428.

Jang, J. (1993). “ANFIS: Adaptive Neuro-Fuzzy Inference System”. *IEEE Transactions System, 23*(3), 665-685.

Jin, J., Zhang, C., & Zhang, Q. (2016). “An enhanced multi-circuit optimization approach for identification of microwave filter parameters”. *In Proc. IEEE MTT-S Int. Conf. Nemer. Electromagn. Multiphys. Modeling Optim. (NEMO)*, (pp. 1-2). Beijing, China.

Kabir, H., Wang, Y., Yu, M., & Zhang, Q. (2008). “Neural network inverse modelling and applications to microwave filter design”. *IEEE Transactions Microwave Theory Techniques, 56*(4), 867-879.

Kabir, H., Zhang, L., Yu, M., Aaen, P., Wood, J., & Zhang, Q. (2010). “Smart modelling of microwave devices”. *IEEE Microwave Magazine, 11*(3), 105-118.

Koziel, S., & Bekasiewicz, A. (2016). “Inverse surrogate modelling for low-cost geometry scaling of microwave and antenna structures”. *IEEE Transactions Microwave Theory Techniques, 33*(4), 1095-1116.

Liu, W., Na, W., Zhu, L., Ma, J., & Zhang, Q. (2017). “A wiener-type dynamic neural network approach to the modelling of nonlinear microwave devices”. *IEEE Transactions Microwave Theory Techniques, 65*(6), 2043-2062.

Mkadem, F., & Boumaiza, S. (2011). “Physically inspired neural network model for RF power amplifier behavioral modelling and digital predistortion.". *IEEE Transactions Microwave Theory Techniques, 59*(4), 913-923.

Na, W., Feng, F., Zhang, C., & Zhang, Q. (2017). “A unified automated parametric modelling algorithm using knowledge-based neural network and l1 optimization”. *IEEE Transactions Microwave Theory Techniques, 65*(3), 729-745.

Pozar, D. (2005). *“Microwave Engineering”* (3rd ed.). New York: Wiley.

Pratihar, D. (2008). *"Soft Computing"*. New Delhi: Narosa Publishing House.

Rahouyi, E., Hinojosa, J., & Garrigos, J. (2006). “Neuro-Fuzzy Modeling Techniques for Microwave Components”. *IEEE Microwave and Wireless Components Letters, 16*(2), 72-74.

Rajasekaran, S., & Pai, G. (2006). *“Neural Networks, Fuzzy Logic, and Genetic Algorithms – Synthesis and Applications”.* New Delhi: Prentice-Hall of India.

Rajasekaran, S., Thiruvenkatasamy, K., & Lee, T. (2005). “Tidal level forecasting functional and sequencial learning neural networks”. *Applied Mathematical Modelling, 30*, 85-103.

Ramadan, A., Costantine, J., Al-Husseini, M., Kabalan, K., Tawk, Y., & Christodoulou, C. (2014). "Tunable Filter-Antennas for Cognitive Radio Applications". *Progress In Electromagnetics Research B, 57*, 253-265.

Rayas-Sanchez, J. (2004). “EM-based optimization of microwave circuits using artificial neural networks: the state-of-the-art". *IEEE Transactions Microwave Theory Techniques, 52*(1), 420-435.

Richard, J., Chandra, M., & Raafat, R. (2007). *“Microwave Filters for Communication Systems: Fundamentals, Design, and Applications”* (2nd ed.). John Wiley & Sons Inc.

Root, D. (2012). “Future device modelling trends”. *IEEE Microwave Magazine, 13*(7), 45-59.

Sugeno, M., & Kang, G. (1988). “Structure identification of Fuzzy Model”. *Fuzzy Sets and Systems, 28*, 15-33.

Tanani, M., & Rebeiz, G. (2010). “High-performance 1.5-2.5 GHz RF MEMS tunable filters for wireless applications”. *IEEE Transactions on Microwave Theory and Techniques, 58*(6), 1629-1637.

Wang, L., & Mendel, J. (1992). “Generating fuzzy rules by learning from examples”. *IEEE Trans. Syst.*, 1414-1427.

Watson, P., & Gupta, K. (1997). “Design and optimization of CPW circuits using EM-ANN models for CPW components”. *IEEE Transactions Microwave Theory Techniques, 45*(12), 2515-2523.

Wong, K. (2002). *“Compact and Broadband Microstrip Antennas”.* New York: Wiley, Interscience.

Yang, Z., Psychogiou, D., & Peroulis, D. (2018). “Design and Optimization of Tunable Silicon-Integrated Evanescent-Mode Bandpass Filter”. *IEEE Transactions on Microwave Theory and Techniques, 66*, 1790-1803.

Zadeh, L. (1965). "Fuzzy Sets". *Information Contr., 8*, 338-353.

Zadeh, L. (1992). Forward. In: Proceedings of the Second International Conference on Fuzzy Logic and Neural Networks., (pp. XIII-XIV). Izuka, Japan.

Zhang, C., Jin, J., Na, W., Zhang, Q., & Yu, M. (2018). "Multivalued Neural Network Inverse Modeling and Applications to Microwave Filters". *IEEE Transactions on Microwave Theory and Techniques, 66*(8), 3781-3797.

Zhang, Q., & Gupta, K. (2000). *“Neural Networks for RF and Microwave Design”.* Boston, MA: Artech House.

Zhang, Q., Gupta, K., & Devabhaktuni, V. (2003). “Artificial neural networks for RF and microwave design – from theory to practice”. *IEEE Transactions on Microwave Theory and Techniques, 51*(4), 1339-1350.

Zhu, L., Zhang, Q., Liu, K., Ma, Y., Peng, B., & Yan, S. (2016). “A novel dynamic neuro-space mapping approach for nonlinear microwave device modelling”. *IEEE Transactions Microwave Theory Techniques, 26*(2), 131-133.

Zurada, J. (1995). *“Artificial Neural Networks”* (Vol. 1). New York: West Publishing Co.